Coupling heat and electricity storage technologies for cost and self-consumption optimised residential PV prosumer systems in Germany

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Cost and self-consumption optimised residential PV prosumer systems in Germany covering residential electricity, heat and mobility demand

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ABSTRACT

Coupling of energy sectors within the emerging residential PV prosumer systems is necessary for an optimised use of the houseowners' produced electricity. But the pure availability of different energy technologies in the system is not enough. The optimising of electricity usage as well as the capacities of PV generators, storage technologies, heat pumps and battery electric vehicles shall be achieved by optimal system configuration and energy handling between the system components. With the simulation of several configurations, not only the best solution in a technical point of view can be achieved, the need of finding the most financially beneficial system composition for single-family houses and tenements is possible. This study provides a detailed model for an average German single-family households and tenements and possible results for the energy transition period until 2050 for an optimised energy system comprised of optimised PV, stationary batteries and different heat storage capacities. The assessment of an optimised system was made by analysing cost saving potentials compared to a 100% grid supply, cost development, self-consumption ratio, electricity and heat cover ratios as well as least cost component capacities. Most noticeable outcomes can be observed by using a vehicle-to-home car, where a car can mostly take over the tasks of a stationary battery and by introducing a solidarity model using this type of car in tenement systems.

Keywords:

Prosumers;
Sector Coupling;
Electric Vehicle;
Energy cost;
Vehicle-to-Home

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1. Introduction

In an ongoing energy transition, households which produce and consume (prosume) their own photovoltaic (PV) electricity will be one of the main drivers for decentralisation of the German energy system. This includes single-family houses in suburbs and rural areas as well as tenements in cities. Recent debates about the use of coal in the German energy system show the need for alternative, environmentally friendly, cheap and decentralised energy supply concepts. PV prosumers will also contribute to reduce the need of electricity transmitted via the grid by about 27% (in 2011), due to the allocation of installed power generation and electricity consumption along with a share of electricity consumption of the residential sector in Germany [1].

Even though the energy system transformation of single-family houses exhibits an upward trend and a milestone of 100,000 installed storage systems was achieved [2], an expansion of the efforts for achieving a fully sustainable energy supply of residential homes must take place. The most efficient approach would be to widen or rather to optimise the use of PV electricity within the system and coupling the different energy sectors of power, heat and transport, which should lead to a maximised self-consumption ratio (SCR) of own PV electricity.

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Abbreviations

ASHP	Air Source Heat Pump
ATCE	Annual Total Cost of Energy
ATGEC	Annual Total Grid Energy Cost
BEV	Battery Electric Vehicle
COP	Coefficient of Performance
DHW	Domestic Hot Water
DoD	Depth of Discharge
DSC	Direct Self-Consumption
GDP	Gross Domestic Product
GSHP	Ground Source Heat Pump
HCR	Heat Cover Ratio
HP	Heat Pump
ICE	Internal Combustion Engine
LUT	Lappeenranta University of Technology
pph	people per household
PV	Photovoltaic
RE	Renewable Energy
SCR	Self-Consumption Ratio
SH	Space Heating
SOC	State of Charge
TES	Thermal Energy Storage
V2H	Vehicle-to-Home

According to [3], nearly half of the energy consumption in buildings relates to the use in space heating and domestic hot water supply. Beneath an optimisation of urban heat supply as mentioned in [4, 5], this represents a possibility for optimising the SCR, as electricity-only optimised PV and battery systems can achieve about 50% [6]. Heat Pumps (HPs) can seize on this fact and are able to act as a coupling technology for the sectors of electricity and heat. The European Union target share for Renewable Energy (RE) of 20% in final energy consumption by 2020 includes 4.9% of final energy from heat pumps and 2.9% from PV [3]. Many European countries, including Germany, accept HPs as a RE source, sourcing surface geothermal energy. Along with the cost reduction potential for this technology and the support of the government, sale figures for HPs are increasing during the last years. In 2017, 78,000 new devices were installed for heating purposes, which means an increase of 17% compared to 2016 [3, 7].

Battery Electric Vehicles (BEVs) are currently one of the fastest developing market segments in the world. In 2017, over 25,000 new BEVs caused an increase of BEV sales in Germany of +119.6% compared to 2016 [8]. An exponential growth in BEV sales in the next years is expected. Nevertheless, electric vehicles are subjected to a main restriction, what is the source of electricity? The full benefits of electricity-driven vehicles by contrast to conventional cars with an Internal Combustion Engine (ICE) can only be achieved if the BEVs are charged with RE sources [9]. As it is well known, cars are stationary most of the time. Especially, cars that are mainly available at home appear to be a waste of storage capacity. The idea of Vehicle-to-Home (V2H) is to make this unused storage capacity available for the residential energy system. This provides an easy way of coupling, power and transport sectors just by adding the possibility of a bi-directional power flow between house and the BEV. Furthermore, HPs and BEVs support finding the most viable energy system, as they are a cheaper option for storing fluctuating energy in smart energy systems then electricity-only storage [10].

The above system is completed with a combined thermal energy storage (TES) for heating as well as potable water supply. The purpose of this study is to combine the mentioned system components and to optimise the power flows between the components for an optimal use of the own produced PV electricity. Analysed are the annual total cost of energy (ATCE), self-consumption ratio (SCR), demand cover ratio (DCR) and heat cover ratio (HCR) for an average German residential households and tenements. With simulation for a whole year, the system can be optimised for a typical yearly solar irradiance for Germany and temperature in the form of heating profiles, which can vary a lot due to the cool temperate climate of Germany.

2. Methods and Data

The model is based on the LUT Energy System model [11, 12, 13]. Additionally, this study is a more precise investigation for Germany of a broader global PV prosumer optimisation [14] and the methodology can be applied to other countries with similar energy demands and housing types as in Germany. The optimisation has been implemented by analysing yearly profiles on an hourly resolution. For the single-family houses the simulation was performed by optimising PV capacities between 1–30 kW_p and stationary battery capacities between 1–50 kWh_{cap} in steps of 1 kW_p and 1 kWh_{cap}, respectively. Every simulation has also been made for TES sizes of 200–1400 litre in steps of 200 litre. Tenements have been taken into account by optimising PV capacities between 1–50 kW_p in 1 kW_p steps and stationary battery capacities between 1–150 kWh_{cap} and TES sizes of 2500 litre, 3500 litre and 4500 litre. Further information about the chosen capacities are provided in the subsections. The simulation software MATLAB was used.

Figure 1 visualises the entire system setup as it was implemented for single-family households. The same structure was used for the tenement simulation, but with values adapted to the characteristics of the tenement system, which are explained in the following subsections in detail. In the figure, black arrows represent electricity flows, whereas orange arrows represent heat flows in form of hot water.

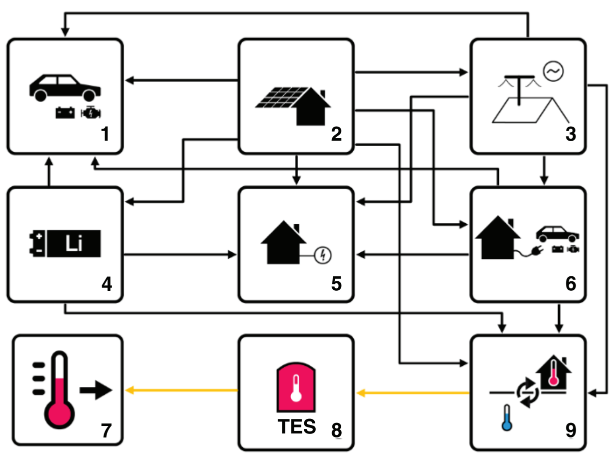

Figure 1: Structure of the PV prosumer model including conventional BEV (1), PV system (2), grid connection (3), stationary battery (4), residential electricity demand (5), BEV with V2H option (6), heat demand (7), thermal energy storage (8) and HP (9)

Table 1: Car usage of the BEV types in the modelled scenarios.

Scenarios	Car 1	Car 2 (V2H)
'Two Cars'	✓	✓
'Only Car 1'	✓	
'Only Car 2'		✓
'No Cars'		

Based on this basic structure, for single-family houses the usage of the BEVs was varied, expressed in four different scenarios. For the scenarios two expressions for the different BEV types are introduced: The 'usually away' car shall be named 'Car 1' and the 'usually at home' car, which included the V2H option, is from now onwards called 'Car 2'. Table 1 shows the implemented scenarios based on those expressions and the car usage.

In this study, all prosumers are considered as average households. This fact mostly relates to the modelling of tenements, as construction years and number of tenants per house underly a quite big variation.

2.1. GDP per Capita and People per Household and Tenement

Most of the relating data was available on a national scale. With the number of citizens, number of households and average people per household (pph) it is possible to calculate the data per household. In [14], a connection between GDP per capita and pph has been derived on a global scale, based on increasing GDP per capita values causing decreasing pph values. For a German single-family households, this derivation results in 2.2 pph in 2015. The projection of the connection results in 2.1 pph from 2020 onwards.

For tenements, it was necessary to find the average housing units per tenement for making conclusions about the average people per tenement. The latest micro census of the German Federal Statistical Office of 2014 [15] includes values for different houses with 1, 2, 3–6, 7–12, 13–20 or more than 21 housing units. Figure 2

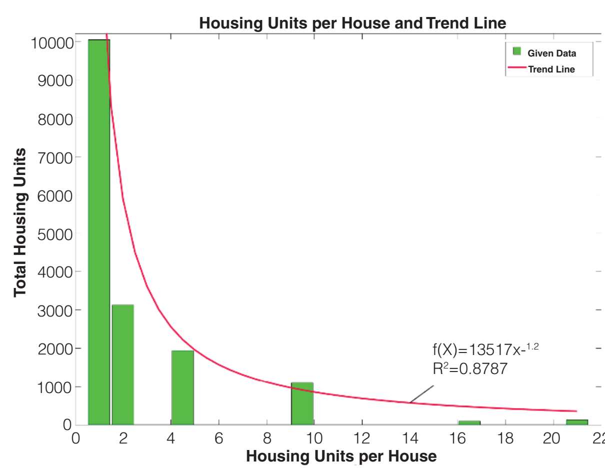

Figure 2: Given data for total number of housing units per house [12] and determined trend line

shows the given values in combination with a determined trend line, which was formed using the MS Excel trend line function, for calculations.

With the given trend line, it was possible to calculate the average housing units per house by using Equation 1. For considering only multi-family houses, the calculation was made with two or more housing units.

$$n_{hu,av} = \frac{1}{n_{flats}} \cdot \int_{2}^{21} x \cdot (13{,}517 \cdot x^{-1.2}) dx \qquad (1)$$

Wherein, $n_{hu,av}$ – average housing units per house; n_{flats} – total number of housing units; x – variable for housing units per house.

Equation 1 leads to an average tenement having 7.4 housing units. With the already mentioned 2.1 pph, the average tenement is home to 15.5 people. This value was also used for the year 2015 as an approximation.

2.2. Solar Data

The input data for PV electricity generation was available for every region in full hourly resolution in the unit of kWh (kWp·h) according to [11, 12]. By multiplying those numbers with the installed PV capacity, the PV generation profile for a given capacity can be obtained.

2.3. Load Profiles

For single-family households, electricity and heat load profiles were taken from [14]. For Germany, it is mostly common to use 'Standardlastprofile' (standard load profiles), which are provided by Bundesverband der Energie- und Wasserwirtschaft e.V. - German Federal Association of the Energy and Water Industry (BDEW) for electricity load forecasting for municipal utilities or energy suppliers. In [14], this load profile was adapted to a profile with a higher morning and evening peak character, as variations of the load during daytime is more common for single-family households, compared to the relatively smooth standard load profile (cf. [16]). However, for several households, the standard load profiles are legitimate [16] and can be used for the tenement simulation. In this study the 'Standardlastprofil H0' from BDEW was taken [17]. Electricity consumption, space heating (SH) and domestic hot water (DHW) for all modelled years and per person can be found in the appendix (Table A1).

In the case of tenements, it was assumed that the DHW is not part of general heat supply and that every flat has a hot water tank for its potable water uses. With an assumed efficiency of $\eta = 1$ the heat was added to the electricity profile for every flat. Additionally, SH profiles had to be adapted to the circumstances of tenements. According to numbers of the German Federal Statistical Office of 2016 [18], average living space per person for residents in tenements was approximately 20% lower than the living space per person for residents living in their own property, of which 80% were represented by single- or two-family houses. The specific SH demand of a reference multi-family house was about 73.6% according to the single-family house values, which together leads to about 41% lower SH demand for a tenement flat.

2.4. Battery Electric Vehicles

As mentioned before, Car 1 is an 'usually away' car, which means that it is mostly used during daytime for working trips and is not available for charging via PV during that time. Therefore, Car 1 must be able to cover its driving demand for a whole week when it is fully charged during weekends. This could be compared to a filled tank of an ICE vehicle. For that reason and the new and upcoming BEV models in sight, battery capacity for Car 1 was fixed to 80 kWh_{cap}. The capacity of Car 2 was set to 60 kWh_{cap}, as this 'usually at home' car is more often available for charging during daytime.

The BEVs are optimised in interacting for charging and in case of Car 2 for discharging or rather in electricity supply of other components. Car 2 gets charged during daytime via PV if available. If PV electricity is available when Car 1 is at home, it gets charged as well, even though Direct Self Consumption (DSC) of electricity for the household has a higher priority. In the morning hours, before the usual leaving time of Car 1, it is checked if electricity can be transferred from the stationary battery to Car 1 and if it is, as much electricity is transferred as possible. If no electricity is left, Car 2 is checked for available energy. Hereby, it is considered that enough electricity is left for Car 2 for a typical daily trip, in case it cannot be charged until it leaves. Only if none of the two electricity storage options can charge Car 1 and the State of Charge (SoC) of the car is below the safety buffer plus one daily trip demand it gets charged via the grid with the amount of electricity which is needed for one typical daily trip. The safety buffer is 25% of the storage capacity and is meant for emergency purposes. The same grid charging behaviour was applied for Car 2. Figure A.1 in the appendix shows a detailed flow chart of the electricity utilisation of the system components, including charging behaviours of the cars as it was implemented for single-family houses. The leaving time of Car 2 for its 3-hour journey was decided randomly within the simulation to create an independent behaviour. Data for leaving times of both cars were taken from [19].

In case of tenements, the operating principle is similar to single-family houses. The tenement system works after a solidarity principle, which means that owners of Car 2 – type cars offer their storage capacity for free. In the beginning of 2017, the total German car stock was around 45.8 million vehicles, majority of them were used privately [20]. With a total German population of 80.7 million people (2015), one person in Germany owns statistically 0.57 cars. Projected to the average people per tenement, the 15.5 people own 8.8 cars, which was rounded up to 9 cars. Furthermore, it was assumed that 4 out of 9 cars are Car 2 - type vehicles and 5 cars are Car 1 - type vehicles. The discharged electricity of the Car 2 - type vehicles is shared between the available cars, as random leaving time was implemented for each Car 2 - type car.

The usual daily car trip demands were calculated according Equation 2. The number of journeys were available from the modelling of the available times as mentioned above. The specific electricity consumption of the BEVs was set to 20 kWh/100 km [19], including discharging efficiency.

$$E_{car,trip} = \frac{yearly\ driving\ distance}{\sum journeys} \cdot E_{cons} \quad (2)$$

Wherein, $E_{car,trip}$ – electricity demand per car and trip and E_{cons} – specific electricity consumption of BEVs.

The discharging and charging efficiency of the BEVs was set to 96.8%, representing the charging and discharging efficiency of Li-Ion batteries of the LUT Energy System model [13]. Driving distances per year range will range between 11,900 and 12,800 km in European Union for the period from 2015 to 2050. According to [21], driving distances were set to 14,000 km/a for Car 1 – type vehicles and 10,000 km/a for Car 2 – type vehicles to better reflect the higher utilisation of Car 1 and lower utilisation of Car 2 – type vehicles.

2.5. Stationary Battery

The type of the stationary battery was also chosen to be Li-Ion battery, as they are increasingly common in residential households. The Depth of Discharge (DoD) was set to 95% and the charging / discharging efficiency as for the BEVs to 96.8%. The stationary battery is envisaged to cover electricity from the household as well as from the Heat Pump (HP) in the evening and night hours, as well as during daytime when DSC is not enough for covering the demand, provided that the stationary battery is charged. In the model, charging of the stationary battery has the highest priority after DSC.

As it can be seen in Figure 1, the stationary battery not only covers electricity demand of the household but is also included in the charging procedure of Car 1 – type cars, as already mentioned in the previous subsection. The purpose of transferring as much electricity as possible to Car 1 – type cars ensures that the cars, which are usually away from home, get enough electricity from the PV system even during winter time. It also has the useful side effect, that the stationary battery is discharged as much as possible in the morning and can be fully charged during daytime, increasing the self-consumption of the PV system. It does not play a role whether load demands cannot be covered by the stationary battery after that, as the charging of Car 1 – type cars via grid would cost the same or even more.

2.6. Heat Pump

For single-family houses the HP was chosen to be a Ground Source Heat Pump (GSHP) for their Coefficient of Performance (COP), which is quite stable throughout the whole year due to mostly homogeneous temperature conditions in the soil. Even though Air Source Heat Pumps (ASHP) are lower in cost, their future role is discussed differently in different scenarios [22]. For reasons of efficiency the GSHP was chosen with the assumption, that enough garden space is available for the collectors. It was modelled as a commercially available HP with the possibility of heating water up to 90°C and a rated power of 7 kW_{el}. For the ease of simulation, the COP was set to a fixed value of 3.8 for nominal operation, which also represents a value from LUT Energy System model [13]. An additional operation mode 'PV additional filling' was implemented, where the HP works at a COP of 3. The purpose of the two different operation modes is explained in the following section.

For tenements, GSHPs are not effective. Based on the calculation and average soil conditions given in [23, 24], a minimum collector area of around 800 m^2 would be needed for an average tenement as assumed below. Therefore, an ASHP was modelled for the tenement system. For tenements the needed output power of the HP had to be estimated, as the energy needed for heating scales differ for larger buildings than for single-family houses. The focus for this estimation was based on future buildings, considering the German Energieeinsparverordnung - German energy saving ordinance (EnEV), with a heat load limit of 40 – 45 W/m^2 in the EnEV of 2009 [24]. Older houses with a year of construction in 1995 and before have a specific heat load of 60 – 130 W/m^2 [25]. For the investigated transition period this value was set to 60 W/m^2 as an average. With the given value for average living space per flat in Germany of 92.9 m^2 [26], the needed thermal energy for heating purposes is 41.3 kW$_{th}$ which was set for the HP output power to 42 kW$_{th}$. For ASHPs, seasonal COPs of 3.6 are expected until 2030 [27]. For the simulation, COP was set to 3.5, which leads to a maximum input power of 12 kW$_{el}$. Devices up to 50 kW$_{th}$ output power and flow temperatures up to 65°C with a COP up to 4.1 for a A7/W35 operation are already available [28]. The PV additional filling option was not included in the tenement model.

The European standards DIN EN 806–2 [29] and DIN EN 1717 [30] recommend a hot water temperature for potable water of minimum 60°C for the avoidance of legionella development. To be on the safe side, a hot water temperature for operation at a nominal value of 65°C was chosen. This consideration combines a water temperature which is as high as necessary for potable water quality and as low as possible for a most efficient HP operation.

2.7. Thermal Energy Storage

The TES is assumed to be a tank-in-tank storage, including capacities for SH and DHW in one device, as they are usually used for solar thermal applications [9]. A standby share of 25% was set for the TES, which guarantees coverage of SH and DHW demands while refilling the storage. Therefore, heat supply is guaranteed even when the TES SoC is quite low, and no refilling request was set off. This refilling request is triggered when the SoC of the TES falls under the 25% standby share. If this request comes during daytime when PV electricity is available, the demand is covered by DSC. If the opposite is the case, the demand gets covered by the stationary battery. If the stationary battery is discharged as well, Car 2 is covering the demand, or in the case of tenement, available Car 2 – type cars take over the shared demand. If none of the energy storage options are able to cover the demand, the refilling demand is covered by the grid. In this case the TES gets filled by the HP with a COP for operation at nominal value as mentioned in section 2.6. Equation 3 describes the calculation of storable thermal energy of the TES.

$$E_{th,cap} = c_{p,water} \cdot V_{TES} \cdot \Delta T \quad (3)$$

Wherein, E_{th} – *thermal energy*; $c_{p,water}$ – specific heat capacity of water (0.0016 kWh$_{th}$/(kg·K), derived from 4.19 kJ/(kg·K)); V_{TES} – storage volume of TES; ΔT – temperature difference (45 K for nominal operation, 70 K for PV additional filling).

The TES as well as the HP are designed for 90°C. Facing the situation that the stationary battery is fully charged, both cars are fully charged or not at home and the TES is charged with 800 litres at 65°C , the PV electricity surplus is normally fed into the grid, which would make no sense for a SCR optimisation, since there is still capacity in the TES available. Therefore, the single-family system has the possibility to fill the TES up at 90°C. Although the COP of 3 for PV additional filling is lower than for nominal operation, the possibility of charging more low-cost energy balances the lower efficiency. With this consideration it is possible to have an added storage capacity of 32 kWh$_{th,cap}$ for an 800 litre tank , which can be used. Figure 3 visualises the TES filling conditions. The idea is to increase SCR at times of very good solar conditions.

The losses of such thermal storage systems are given between 1.6 kWh$_{th}$ and 2.5 kWh$_{th}$ per 24h (cf. [31]). Applied to an 800 litre TES used in this model, results in thermal energy losses of about 0.15% per hour, considering a fully charged TES. For an easier simulation, this value was applied independently of the SoC and

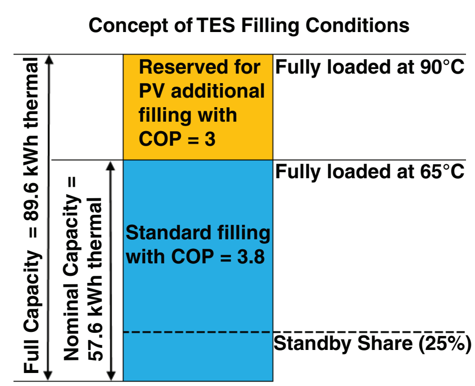

Figure 3: Concept of TES filling conditions for the two operation modes of the HP as an example for an 800 litre storage of a single-family house

TES size. The efficiency assumptions for all relevant system components are listed in Table A2.

For getting an appropriate TES size for tenements it was resorted to SH demands of the year 2015. Single-family houses have an SH demand of 13.84 MWh/a, leading to a 57.8 litre/MWh ratio using a middle sized 800 litre storage. The modelled tenement has a specific heat demand of 60.27 MWh/a. By using the above-mentioned ratio, the resulting TES size is about 3500 litre. As for the tenement model, DHW demand is not part of the heat demand, the simulation was also made for a 2500 litre TES as well as for a 4500 litre TES, so it will be possible to compare if a smaller or larger TES is beneficial.

2.8 Financial Target Function

The ATCE is calculated by applying Equation 4, which has to be minimised for the year.

$$ATCE = \sum_{i}^{technology} (Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + cost_{grid} - income_{feedin} \quad (4)$$

Wherein, *ATCE* – annual total cost of energy; *Capex* – investment cost for technology; crf – annuity factor; $opex_{fix}$ – fixed operational expenditures; $opex_{var}$ – variable operational expenditures; $E_{throughput}$ – energy handling of component (e.g. discharged energy of the battery); $cost_{grid}$ – cost of remaining electricity supplied by the grid; $income_{feedin}$ – income for PV electricity fed-in to the grid.

For comparison of an annualised energy cost, Equation 5 was applied for a 100% grid supply of the energy system without a PV system and stationary battery. This has to be minimised for an entire year. For 100% grid supply, Car 2 - type cars are assumed to be a normal BEV, as the V2H application for grid supply may not be beneficial. The HP operates at a nominal value for grid supply, to keep the yearly cost as low as possible.

$$ATGEC = \sum_{i}^{HP,TES} (Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + \left(\frac{E_{th,DHW} + E_{th,SH}}{COP_{nom}} + E_{el,house} + E_{el,car1} + E_{el,car2} \right) \cdot price_{grid} \quad (5)$$

Wherein, *ATGEC* – annual total grid electricity cost; $E_{th,DHW}$ – annual thermal energy for domestic hot water demand; $E_{th,SH}$ – annual thermal energy for space heating; COP_{nom} – Coefficient of Performance of HP for operation at nominal value; $E_{el,house}$ – annual electricity consumption of household; $E_{el,car}$ – annual electricity demand for driving.

Assumptions for financial values of system components and grid prices are based on the LUT Energy System model and available (cf. [11, 12, 13], Table A.3, A.4). For BEVs, storage costs are not considered as it is assumed that the batteries are paid with the car anyway. For all years, a feed-in reimbursement of 0.02 €/kWh was used. Due to assumed grid limitations, the feed-in reimbursement was assumed to be paid for feed-in electricity up to 50% of the generated electricity.

The feed-in reimbursement is not relevant for households in the tenement as it was assumed that the income for fed-in electricity is kept by the plant operator. Further, the annual total cost of energy per housing unit was calculated in three different ways, for a housing unit owning a Car 1 - type vehicle, for a housing unit owning a Car 2 - type vehicle and for a housing unit owning no car, so the basic value for every housing unit, on average, is the same, including electricity and heat.

3. Results and Discussion

In the following the results of the system simulations are presented regarding financial outcomes, cover ratios and least cost systems.

3.1. Total Cost of Energy and Cost Drop Potential

The results for single-family houses in Germany is shown in Figure 4. The ATCE differs in 2015 for the ‘Two Cars Scenario’ from 5800 €/a for the 200 litre system to 6350 €/a for the 1400 litre system. For the ‘Only Car 1 Scenario’, the limits are 5900 €/a and 6360 €/a, for the ‘Only Car 2 Scenario’ 5430 €/a and 6000 €/a and for the ‘No Cars Scenario’ 5450 €/a and 6060 €/a.

Overall, the upper and lower limits do not differ much between the scenarios. Until 2050, impact of different TES sizes on the ATCE is minimised. The difference in ATCE of a 1400 litre system, compared to a 200 litre system in 2015 is about 550 € for the ‘Two Cars Scenario’ and the ‘Only Car 2 Scenario’, 460 € for the ‘Only Car 1 Scenario’ and 610 € for the ‘No Cars Scenario’. This will decrease until 2050 to about 150 €, 120 €, 140 € and 230 € for the ‘Two Cars-, Only Car 1-, Only Car 2-, and No Cars Scenario’, respectively.

The decreasing investment cost for the TES has a clear impact on the ATGEC. By only using one car, the ATGEC decreases for big TES capacities until 2030.

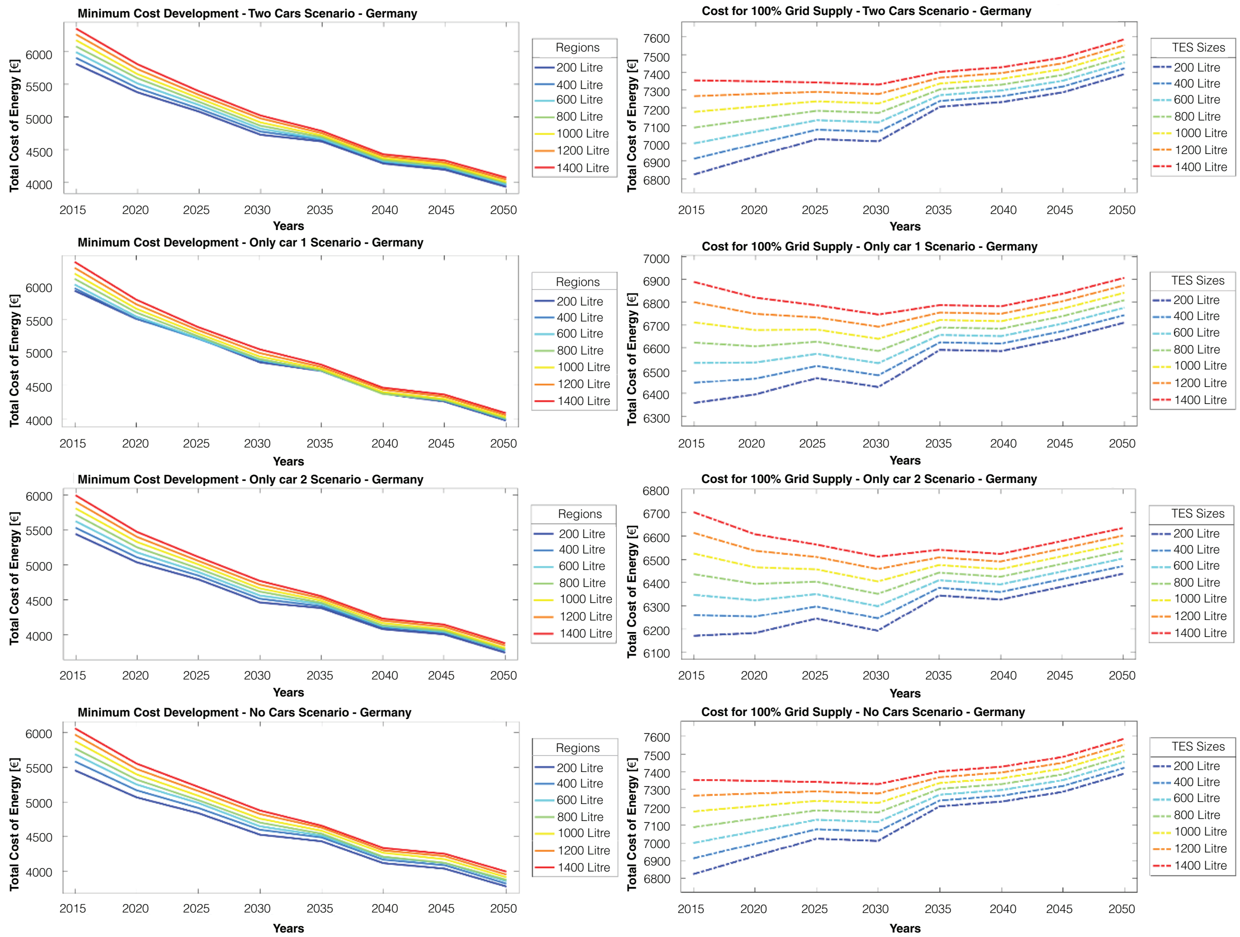

Figure 4: Development for ATCE for least cost system (left) and a full grid supply (right) for the different TES sizes and for 'Two Cars Scenario' (top), 'Only Car 1 Scenario' (center top), 'Only Car 2 Scenario' (center bottom) and 'No Cars Scenario' (bottom)

For middle sized TES capacities, the ATGEC nearly stay the same as in 2015 and increase for small TES capacities. However, the effect on the cost saving potential of the systems is quite negligible, as it can be seen in Figure 5 for the 'Two Cars Scenario'. The figures for all scenarios can be found in the appendix (Figure A.2). The sum of possible savings is mostly dependent on the specific year in absolute as well as relative values. All systems for Germany are already profitable in 2015.

By not using any car, most of the cost could be saved in 2015 with a possible saving potential of about 1300 €/a, compared to the 100% grid supply scenario. This is not surprising as energy demand from both the cars burdens the PV system considerably as the attempt is to charge BEVs with maximum of PV energy. Nevertheless, for the 'Two Cars Scenario' it would be possible to save about 1000 €/a. For the 'Only Car 1 Scenario' the saving

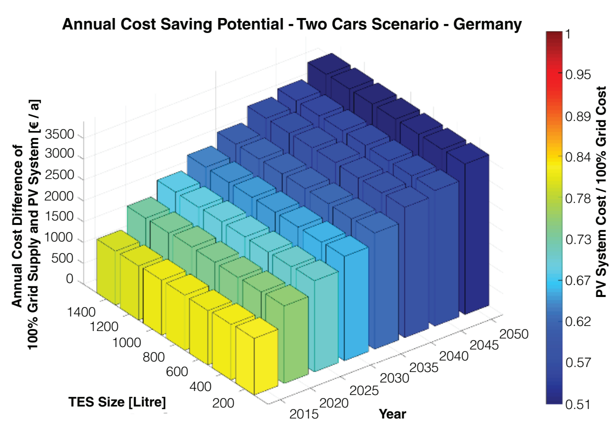

Figure 5: Saving potential of ATCE compared to a 100% grid supply (ATGEC) for all modelled years and TES sizes of a German single-family house for the 'Two Cars Scenario'

potential in 2015 was about 500 €/a and for the 'Only Car 2 Scenario' about 700 €/a. In 2050, for the 'Two Cars Scenario' and the 'No Cars Scenario' it will be possible to save about 3500 €/a while for the scenarios with only one car a saving potential of about 2750 €/a is possible.

Until 2050, it will be possible to reduce the ATCE over 2000 €/a. The differences between the scenarios are not significant. For the ATCE drop the differences are mainly noticeable for the different TES sizes. Among all the scenarios, system with the largest TES capacity shows a high cost drop potential. With 2015 as a reference value a drop is enabled for the ATCE in 2050 by around 1800 €/a for the 200 litre system up to 2300 €/a in the 'Two Cars Scenario'. For the 'Only Car 1 Scenario' the cost drop of about 1900 €/a (200 litre) and 2300 €/a (1400 litre), for the 'Only Car 2 Scenario' of about 1600 €/a (200 litre) and 2100 €/a (1400 litre) and for the 'No Cars Scenario' of about 1600 €/a (200 litre) and 2000 €/a (1400 litre) can be obtained. The values for all years and TES sizes are shown in Figure 6 exemplarily for the 'Two Cars Scenario'. Figures for the other scenarios are attached to the appendix (Figure A.3).

The results for the German tenement system per housing unit of the minimum cost development as well as the development of a 100% grid supply is shown in Figure 7. Most noticeable is the fact, that the different TES sizes from 2500 to 4500 litre are not causing much differences even for a 100% grid supply. Compared to a single-family house the ATCE are much lower. One of the biggest influencing factors is the much lower SH demand. Additionally, the housing units share the investment cost of the system components. In 2015, ATCE per year differ at about 2500 €/a up to 2450 €/a. The cost depending on the car usage and TES size overlaps within this range (cf. Figure 7). The lowest cost can be achieved for a 2500 litre TES and using no car. The highest cost has to be expected for using a car, no matter which type, and for the biggest TES of 4500 litre. Results for the 3500 litre TES are in between. This leads to the presumption that the differences for ATCE are mostly dependent on the share of investment cost per housing unit. If it would be assumed that a bigger TES would have lower investment cost per installed kWh_{cap},

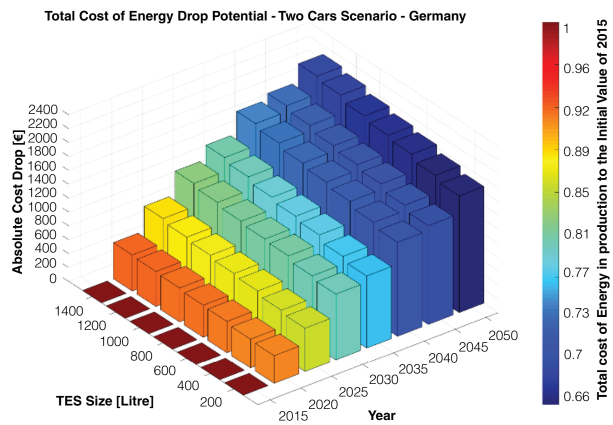

Figure 6: Drop potential in ATCE compared to the initial value of 2015 for all modelled years and TES sizes for a German single-family house in the 'Two Cars Scenario'

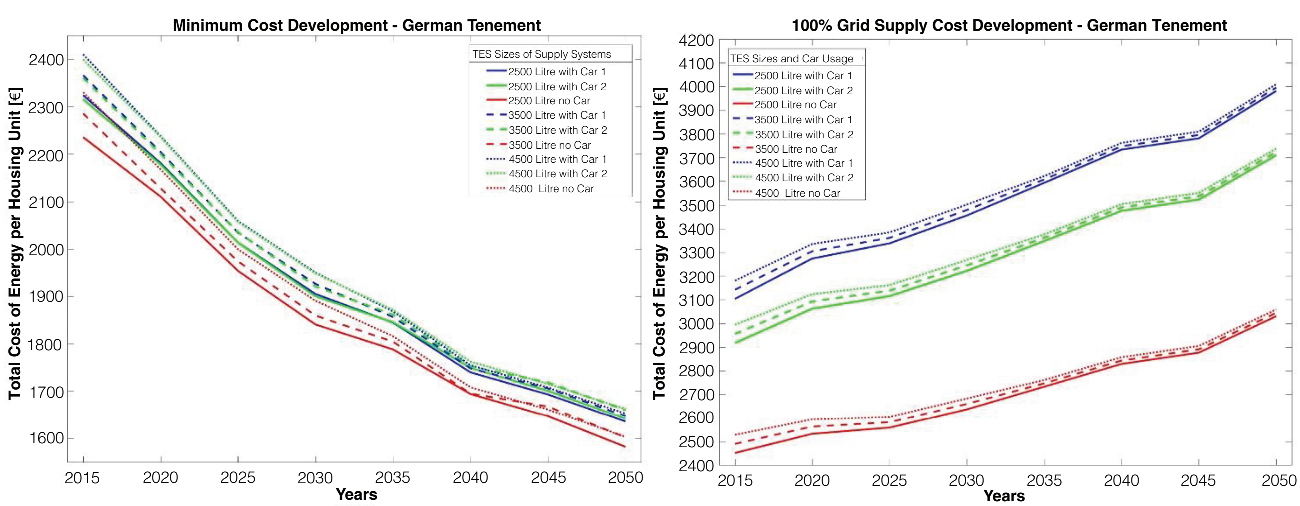

Figure 7: Development for ATCE per housing unit in a tenement (left) and development for ATGEC per housing unit (right)

the difference could vanish. Even though, the cost drop potential per household is not as high as for single-family houses. In 2050, ATCE can be dropped by up to 800 €/a to about 1650 €/a for a single household. When using no car, the difference of varying the thermal storage capacity from 3500 litre to 4500 litre is significant. Even though, cost for using different car types do not differ very much around the 1650 €/a mark. However, the ATGEC is higher for all usages and TES sizes, so the system is profitable for a household already in 2015.

3.2. Self-Consumption Ratios

For all investigated TES sizes of single-family houses nearly the same values for SCR can be achieved. The biggest difference can be obtained for the 'Only Car 1 Scenario', where the SCR differs in 2015 by about $10\%_{abs}$. The consistency of the SCR lasts for the whole energy transition period and for all scenarios, as it can be seen in Figure 8 for the case of the 'Two Cars Scenario'. The other scenarios can be found in the appendix (Figure A.4). The 'No Cars Scenario' includes the highest SCRs among all with over 90% in 2015 to about 45%–50% in 2050 with an almost linear development. At the 'Only Car 1 Scenario', a nearly linear decrease can be seen, too, with SCRs from around 72%–82% in 2015 and 35%–40% in 2050. With scenarios including Car 2 the values for 2015 are between 80% and 90% and end up at 40%–43% for the 'Two Cars Scenario' and at 35%–40% for the 'Only Car 2 Scenario'. A clear dependence of the SCR on the investigated TES sizes cannot be found, as the variation of PV and stationary battery capacities adapt the system in a proper way.

The achievable SCRs of the whole tenement system, by which the whole tenement is meant and not a single housing unit, are slightly higher than for a single-family house. Beginning with relatively high SCRs in 2015 of 85%–90% for the different TES sizes, the development ends in 2050 at slightly over 50%, as shown in Figure 8. A dependence on the used TES sizes for the tenement system can again not be determined. Without the need to supply DHW demand of the people living in the tenement, a lower SCR would be expected as less energy has to be transformed from electricity into heat. But as the tenement system with its ASHP does not have the possibility of heating water up to 90˚C, more time and more electricity is needed to fill the TES, which prevents higher SCRs. Additionally, less energy is stored in the TES which leads to more load hours of the HP for refilling the storage, mostly during the winter period. In the summer, much energy is fed into the grid due to a quite low SH demand.

3.3. Demand and Heat Cover Ratios

For the DCR, results with regard to dependence on the installed TES size are quite similar to the SCR results. No obvious dependence on the TES size is identifiable, cf. Figure 9 for the 'Two Cars Scenario'. A real benefit for the DCR can be achieved at the beginning of the investigated period by using both cars. With 77%–80%, the 'Two Cars Scenario' achieves the highest DCRs for 2015, followed by the 'No Cars Scenario' with 70%–75%. The 'Only Car 2 Scenario' starts with about 70% for all TES sizes. The least favourable results in 2015 occur for the 'Only Car 1 Scenario' by having the most

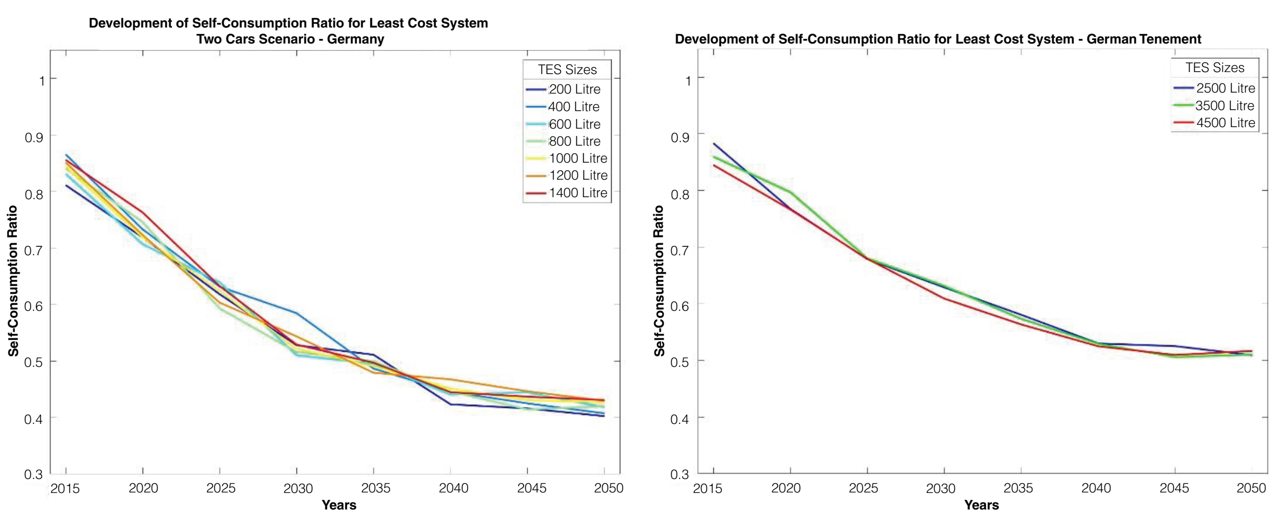

Figure 8: Development of SCR for single-family system (left) at the 'Two Cars Scenario' and for the tenement (right) for all years and TES sizes

values at about 65%–68%. In 2050, no significant differences between the scenarios can be observed. Overall high DCRs of about 95% are possible.

Figure 9 also shows the development for the HCR exemplarily for the 'Two Cars Scenario'.

Unlike the SCR and DCR, for some scenarios a small dependence of the TES size can be spotted. Although, the differences between the TES sizes are not very big, slightly higher HCRs can be reached with a bigger storage for thermal energy. In addition, higher HCRs are able by using Car 2 as an energy supply option for the HP. For the 'Two Cars Scenario' the range is at 50%–58% and for the 'Only Car 2 Scenario' a little bit lower at 47%–50%. At the 'Only Car 1 Scenario' small TES sizes from 200 litre to 600 litre are able to reach 40%–53% of the annual heat demand with PV electricity. Middle sized and big capacities can cover about 55%–58% of the heat demand. The lowest HCRs occur for the 'No Cars Scenario' with values for 2015 of 22% up to 43%. In 2050 the difference between the scenarios is not that big as in 2015. All values can be stated at around 90%. The results of the 'Two Cars Scenario' and the 'No Cars Scenario' are a little bit lower at about 85%–90%. For the other two scenarios the values differ between 88% and 95%, whereas bigger sizes for the TES lead to higher HCRs. Figures A.5 and A.6 in the appendix show the DCRs and HCRs for all single-family scenarios.

For covering the electricity demand of tenement prosumers, about 70% can be covered with own produced electricity in 2015. This ratio increases until 2050 up to 90% for all TES sizes, as it can be seen in Figure 10. The development of the HCR, also shown in Figure 10, increases with the customarily course from 35%–42% in 2015 up to around 75% in 2050. The numbers of HCR for the tenement system is $10\%_{abs}$ to $15\%_{abs}$ below those of a German single-family house. A possible reason is the lower COP of the ASHP with which it will not be able to cover the whole SH demand during the winter when the available PV electricity is already low. For tenements, both parameters DCR and HCR can be interpreted independently on the installed TES size.

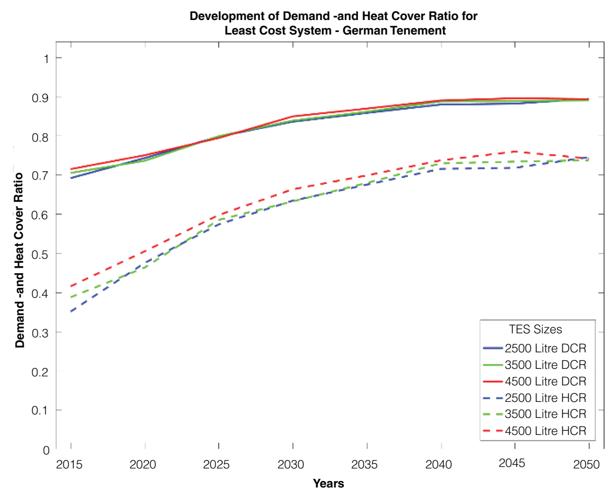

Figure 10: Development of the DCR and HCR for the German tenement system for all TES sizes and years.

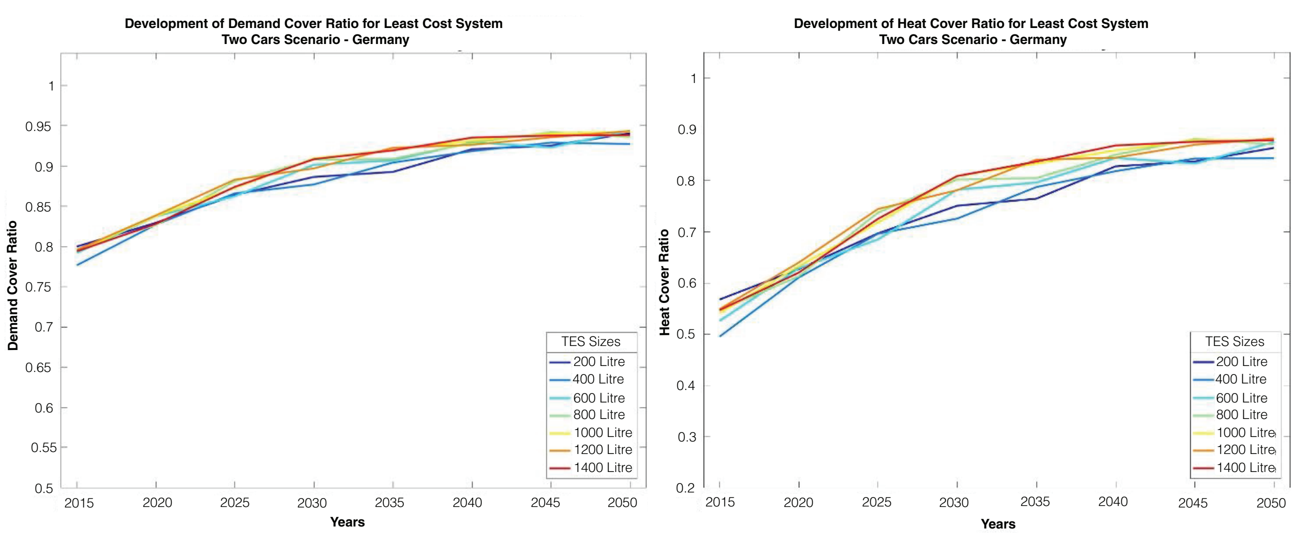

Figure 9: Development of DCR (left) and HCR (right) for all TES sizes and years for the 'Two Cars Scenario'

Additionally, it must be mentioned that the DHW demand is part of the electricity demand and its supply is considered with the DCR.

3.4. Least Cost System Design

For all scenarios of the single-family house, large PV capacities will be part of a least cost system independent on the installed TES size. In 2015, for the 'Only Car 1, Only Car 2 and No Cars Scenario' the most economic PV capacity was from 5 kW_p – 10 kW_p. Only for the 'Two Cars Scenario', capacities over 10 kW_p were profitable.

As it can be seen in Figure 11, in this case for the 'Only Car 1 Scenario', and in Figure A.7 for all scenarios, the least cost PV capacity increases almost linearly until 2050. Again, a clear dependence on the TES size cannot be detected for the whole transition period. In 2050, for the 'Two Cars and Only Car 1 Scenario', nearly the maximum of the investigated PV capacity of 30 kW_p will be necessary. For the 'Only Car 2 Scenario' the results in 2050 are 25 kW_p–30 kW_p and for the 'No Cars Scenario' 23–27 kW_p.

The most relevant parameter for adjusting the system, at least for the 'Only Car 1 and No Cars Scenario', is the installed capacity of the stationary battery. As Figure 11 shows for the 'Only Car 1 Scenario', the battery capacity for the least cost system differs a lot between the TES sizes. All scenarios can be found in Figure A.8 in the appendix. A substantial difference can be noticed for scenarios with and without Car 2. Almost nil or only small battery capacities up to 5 kWh_{cap} in most cases will be necessary for the 'Two Cars and Only Car 2 Scenario' from 2015 until 2050. For the 'Only Car 1 Scenario' a clear dependence of the least cost stationary battery on the thermal storage option occurs. Small TES sizes from 200 litre to 600 litre will need battery capacities of 25-30 kWh_{cap} and bigger sizes of about 12-20 kWh_{cap} in 2050, starting in 2015 with 1 kWh_{cap} . The optimisation detects the needs of the system and substitutes the lack in storage capacity for thermal energy with storage capacity for electricity.

For the 'No Cars Scenario', difference between the different TES sizes is not that clear as for the 'Only Car 1 Scenario'. Without charging Car 1 via the stationary battery the substitution of the lacking TES capacity is the only driver for different battery capacities. In this scenario, all developments for the different TES sizes begin with 1 kWh_{cap} in 2015 and increase up to 8 kWh_{cap} until 2050 for 1400 litre and up to 17 kWh_{cap} for 200 litre, 600 litre and 1200 litre, respectively. Without the cost free storage, capacity of Car 2 the stationary battery is therefore the most important variable for optimising single-family systems. The PV capacity stays nearly the same for different TES options.

Even though V2H cars are used in the tenement model, stationary batteries will play a larger role in such systems. Beginning in 2025, the need for stationary battery capacities increases until 2050 up to 55 kWh_{cap} for the 2500 litre option and about 48 kWh_{cap} for the

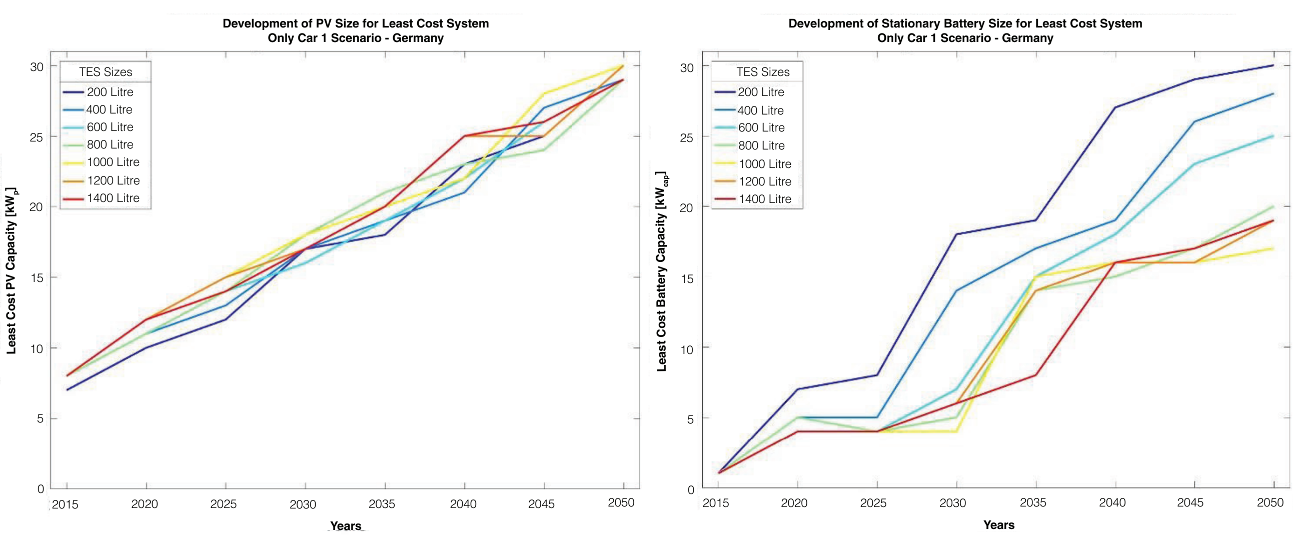

Figure 11: Development of the least cost PV capacity (left) and least cost stationary battery capacity (right) for the 'Only Car 1 Scenario', all years and TES sizes

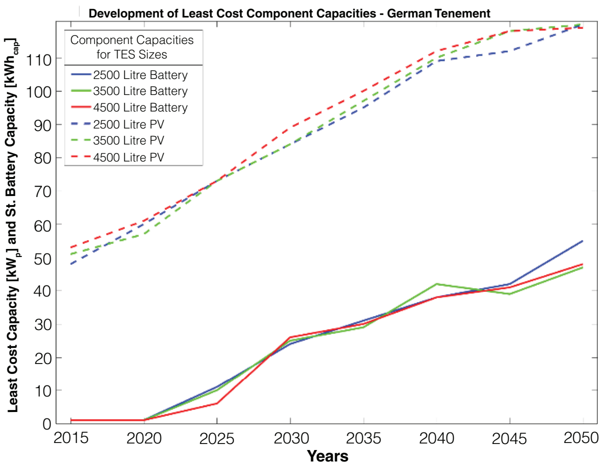

Figure 12: Development of the least cost system design for a German tenement for all years and TES sizes

3500 litre and 4500 litre system. As it can be seen from Figure 12 the dependence on the installed TES size is not noticeable within the investigated period. As storing electricity has the priority in the model, the stationary batteries will be needed to store the electricity and is later discharged for supplying the HP as the PV additional filling option is not available for the tenement.

The PV capacity increases almost linearly from around 50 kW_p in 2015 up to the biggest possible capacity of 120 kW_p in 2050. By including lot of cars in the system, high PV capacities are beneficial for supplying cars with cheap PV electricity. A significant dependence of the PV capacity on the installed TES size cannot be observed, even though the smallest TES size causes slightly smaller capacities from 2030 to 2045 and vice versa, as it can be seen in Figure 12.

4. Conclusion

Coupling the sectors of power, heat and transport even on a small scale will be highly beneficial for PV prosumers, particularly for decreasing ATCE compared to a 100% grid supply for both the systems: Single-family houses and tenements in Germany. An absolute optimisation of ATCE and SCR at the same time is nearly impossible, so it is necessary to find a compromise. Nevertheless, the best possible SCR is achievable for all TES sizes and by optimising PV and stationary battery capacity, the SCR does not get influenced by the installed TES size. Furthermore, the type of the used BEV for single-family houses is secondary. Primarily, the decision if a BEV is included in the system or not makes the biggest difference. Using cars with a V2H option is very beneficial. For single-family houses it is even possible to subsidise the stationary battery, if such type of car is available for the system for an appropriate amount of time. Very high DCRs are achievable for both system types, caused by combining different storage types and optimising the multi-storage system.

For both systems, a middle-sized TES is the best option, regarding the TES sizes investigated in this study, as those again are the best compromise, in this case for absolute and relative cost drop and saving potentials, at least for the single-family house system. Combined with the used HPs, these systems are able to reach high HCRs, even by using an ASHP for a tenement.

Additionally, it would be possible to optimise the systems further by including long-term storage, as it is already available for residential and commercial facilities [32, 33]. Summarising the results, residential rooftop PV systems will be a very cost-efficient possibility for delivering energy to households and for self-sufficiency of energy.

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Appendix 1: Data Tables

Table A.1: Annual energy consumption per capita for electricity, domestic hot water and space heating (single-family house based) for all modelled years

	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Electricity	[MWh_{el}/a]	1.86	1.83	1.82	1.87	1.90	1.97	2.02	2.12
DHW	[MWh_{th}/a]	0.68	0.69	0.70	0.72	0.73	0.74	0.75	0.76
SH	[MWh_{th}/a]	6.59	6.67	6.53	6.65	6.66	6.57	6.67	6.77

Table A.2: Efficiency assumptions for the storage and energy conversion technologies

	Unit	Stationary Battery	TES	Car 1	Car 2	HP
Charging	[%]	96.8	100	96.8	96.8	–
Discharging	[%]	96.8	100	–	96.8	–
Standby losses	[%/h]	0	0.15	0	0	–
Electricity-to-Heat conversion nominal COP, GSHP	–	–	–	–	–	3.8
Electricity-to-Heat conversion PV additional filling COP, GSHP	–	–	–	–	–	3.0
Electricity-to-Heat conversion nominal COP, ASHP	–	–	–	–	–	3.5

Table A.3: Financial assumptions for the system technologies

Financial Assumptions									
	Unit	2015	2020	2025	2030	2035	2040	2045	2050
PV Rooftop									
Capex	[€/kW_p]	1360	1090	890	760	680	610	550	500
Opex fix	[€/(kW_p·a)]	20	16	13	11	10	9	8	8
Lifetime	[a]	30	30	35	35	35	40	40	40
Stationary Battery									
Capex	[€/kWh_{cap}]	600	300	200	150	120	100	85	75
Opex fix	[€/(kWh_{cap}·a)]	24	9	5	3.75	3	2.5	2.125	1.875
Opex var	[€/($kWh_{through}$·a)]	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Lifetime	[a]	15	20	20	20	20	20	20	20
Heat Pump									
Capex	[€/kW_{el}]	1600	1500	1500	1400	1400	1300	1300	1200
Opex fix	[€/(kW_{el}·a)]	20.6	19.5	19.5	17.9	17.9	17.4	17.4	16.9
Lifetime	[a]	20	20	20	20	20	20	20	20
Thermal Energy Storage									
Capex	[€/kWh_{cap}]	50	40	30	30	20	20	20	20
Opex fix	[€/(kWh_{cap}·a)]	0.75	0.6	0.45	0.45	0.3	0.3	0.3	0.3
Lifetime	[a]	25	25	25	25	30	30	30	30

Table A.4: Electricity prices for grid supply.

Unit	2015	2020	2025	2030	2035	2040	2045	2050
[€ / kWh_{el}]	0.2330	0.2649	0.2784	0.2926	0.3075	0.3232	0.3232	0.3397

Appendix 2: Flow Chart for BEV charging behaviour

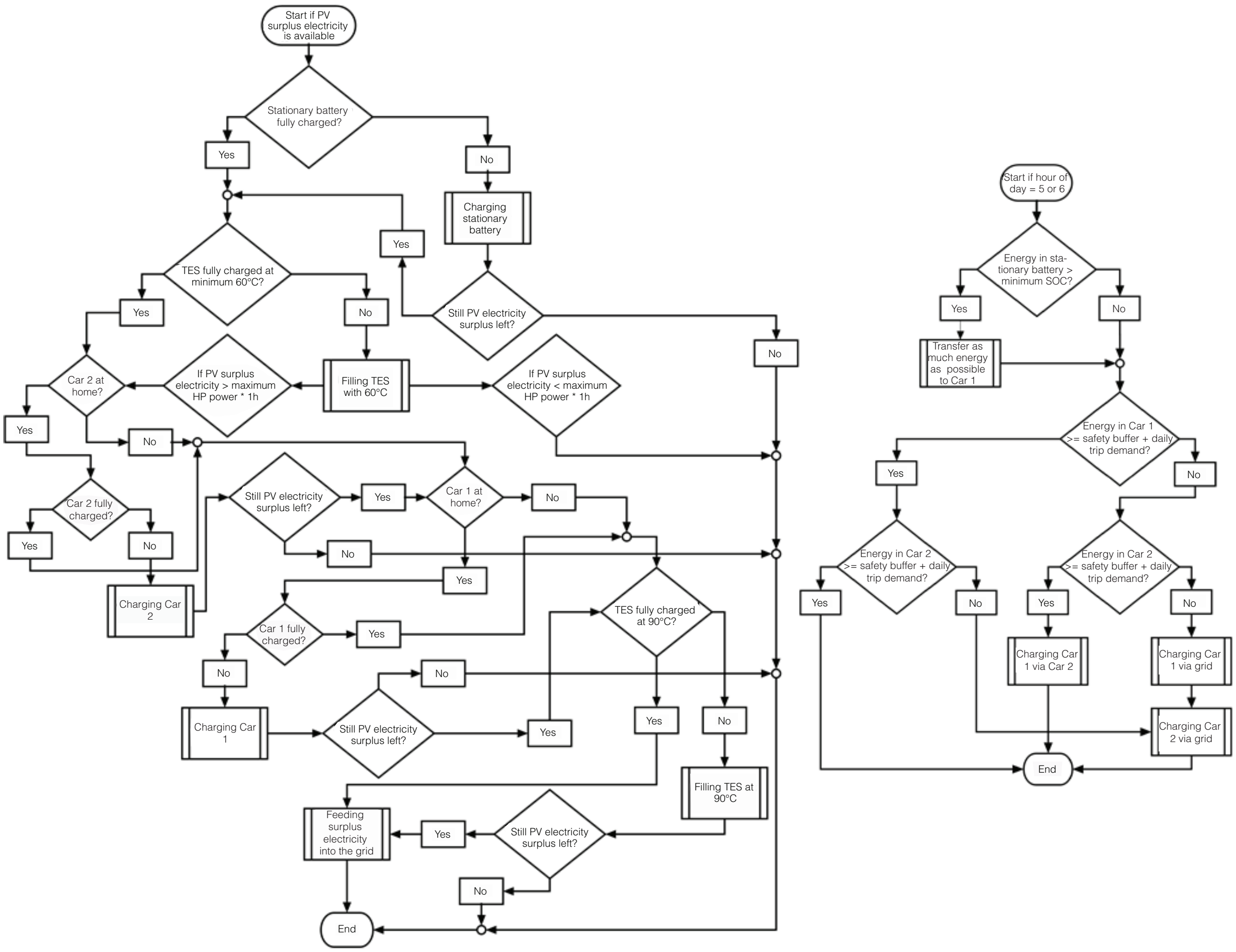

Figure A.1: Flow charts indicating the sequential operation of the components of a PV prosumer household. PV electricity utilisation (left) and charge transfer between the BEVs (right)

Appendix 3: Result Figures

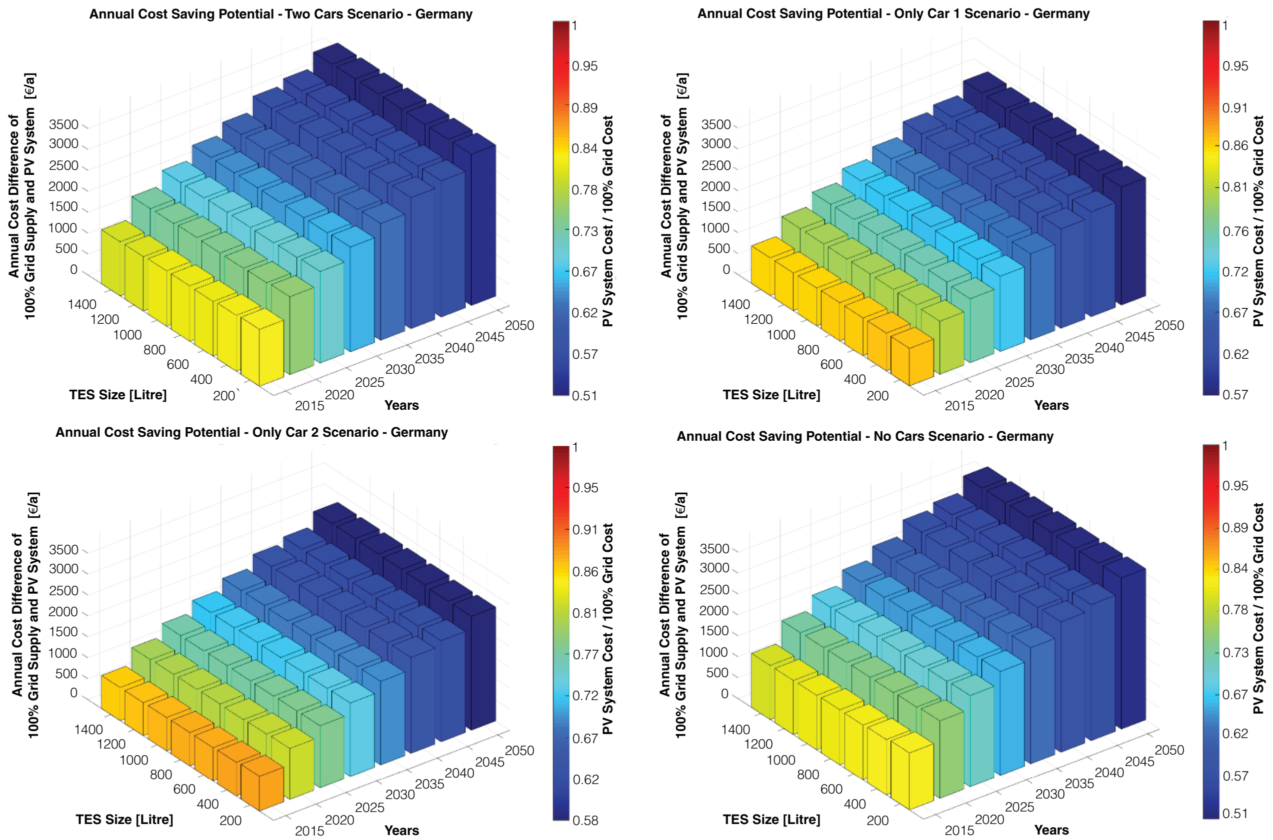

Figure A.2: Absolute and relative saving potential of ATCE compared to a 100% grid supply (ATGEC) for different TES sizes of the single-family system for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right)

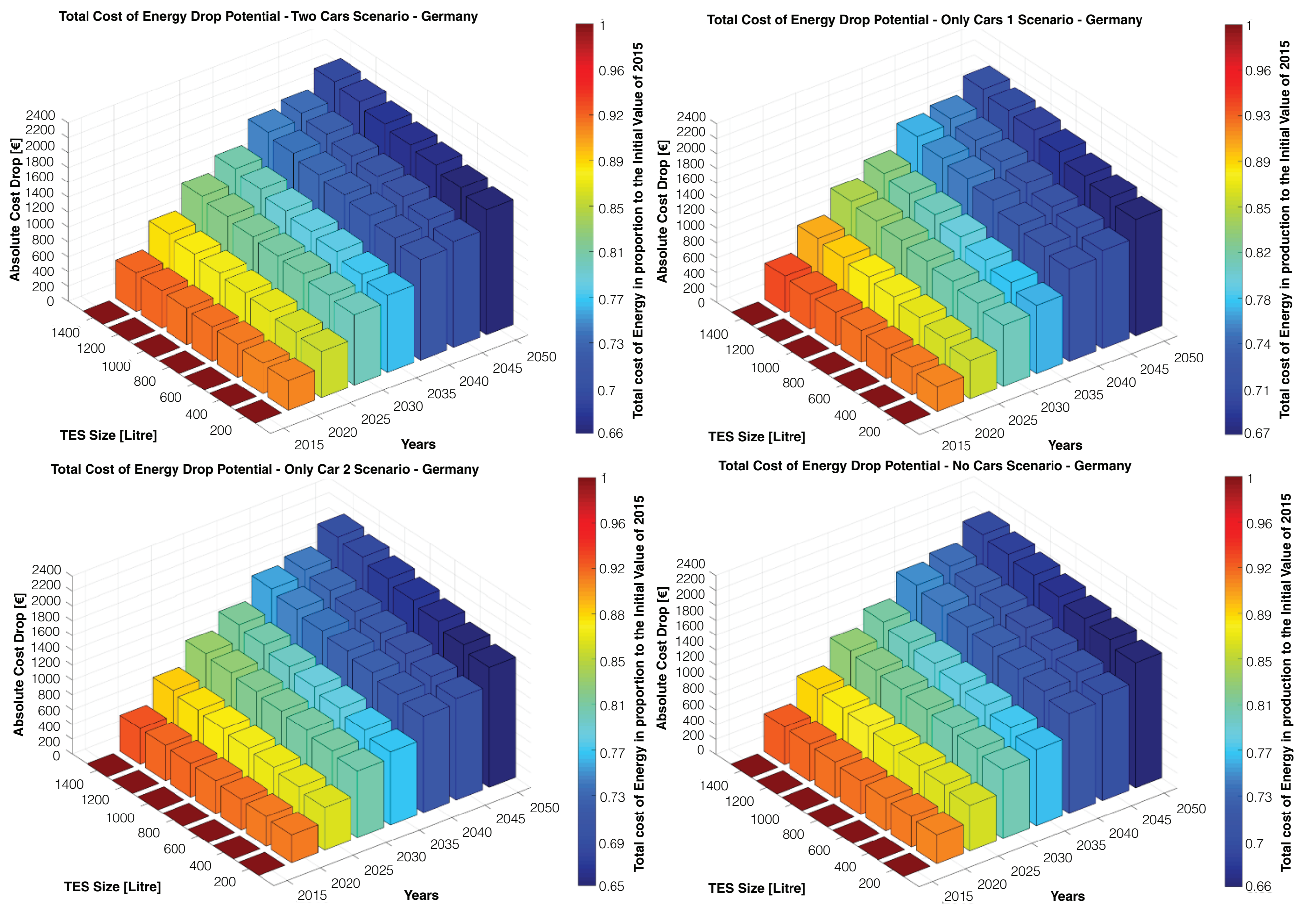

Figure A.3: Absolute and relative drop potential of ATCE compared to the initial value of 2015 for different TES sizes of the single-family system for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right)

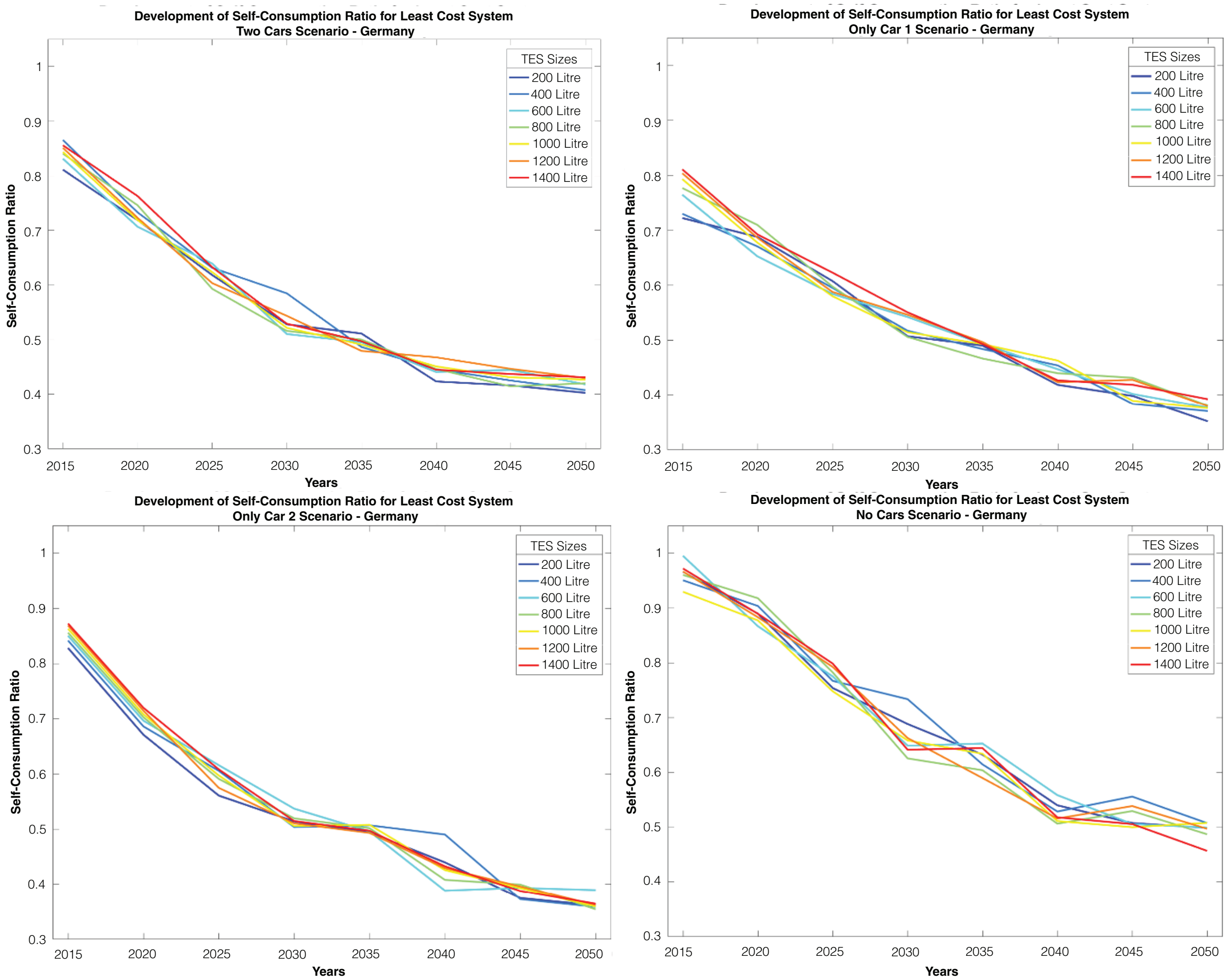

Figure A.4: Development of SCR of the single-family system for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right)

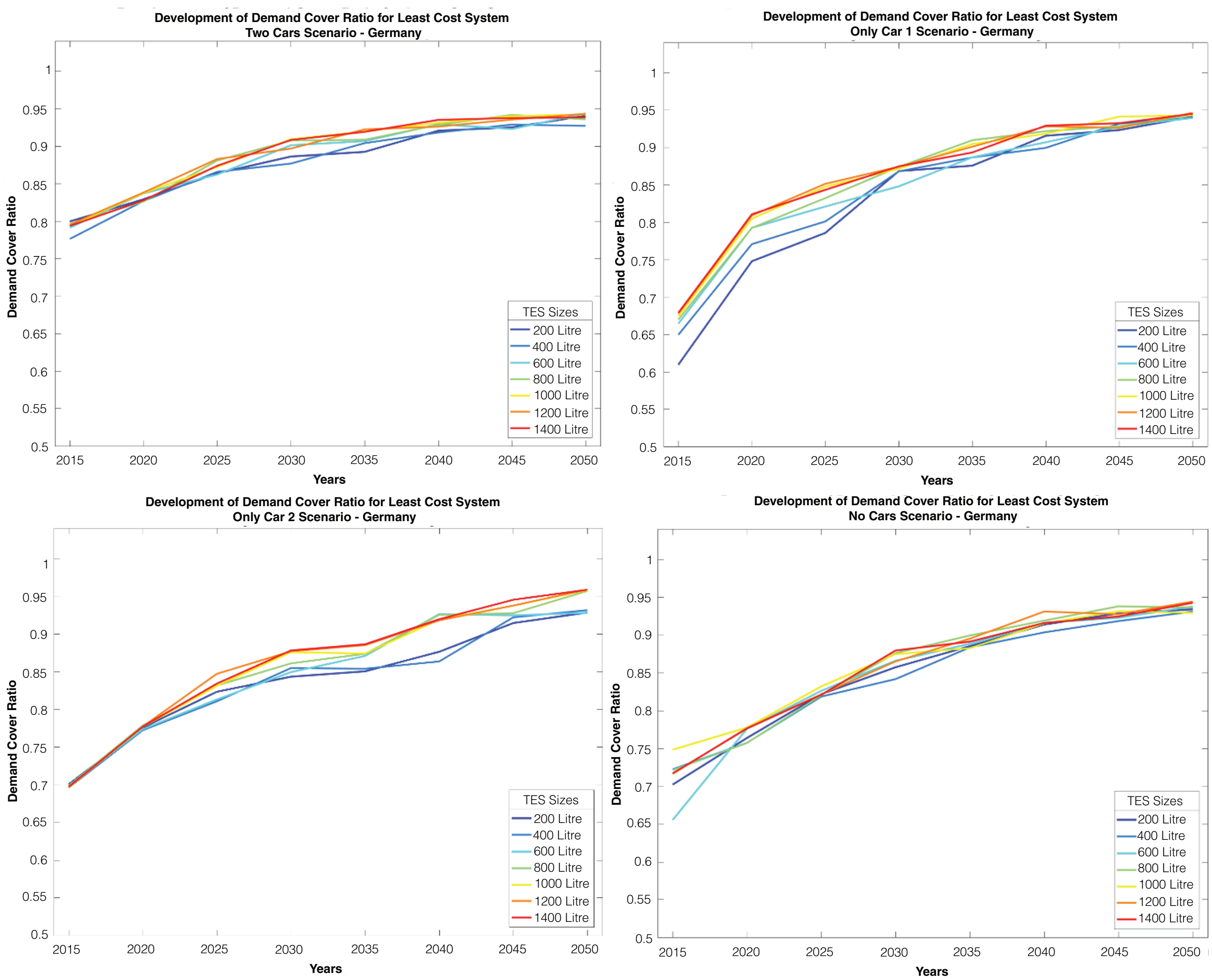

Figure A.5: Development of DCR of the single-family system for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right)

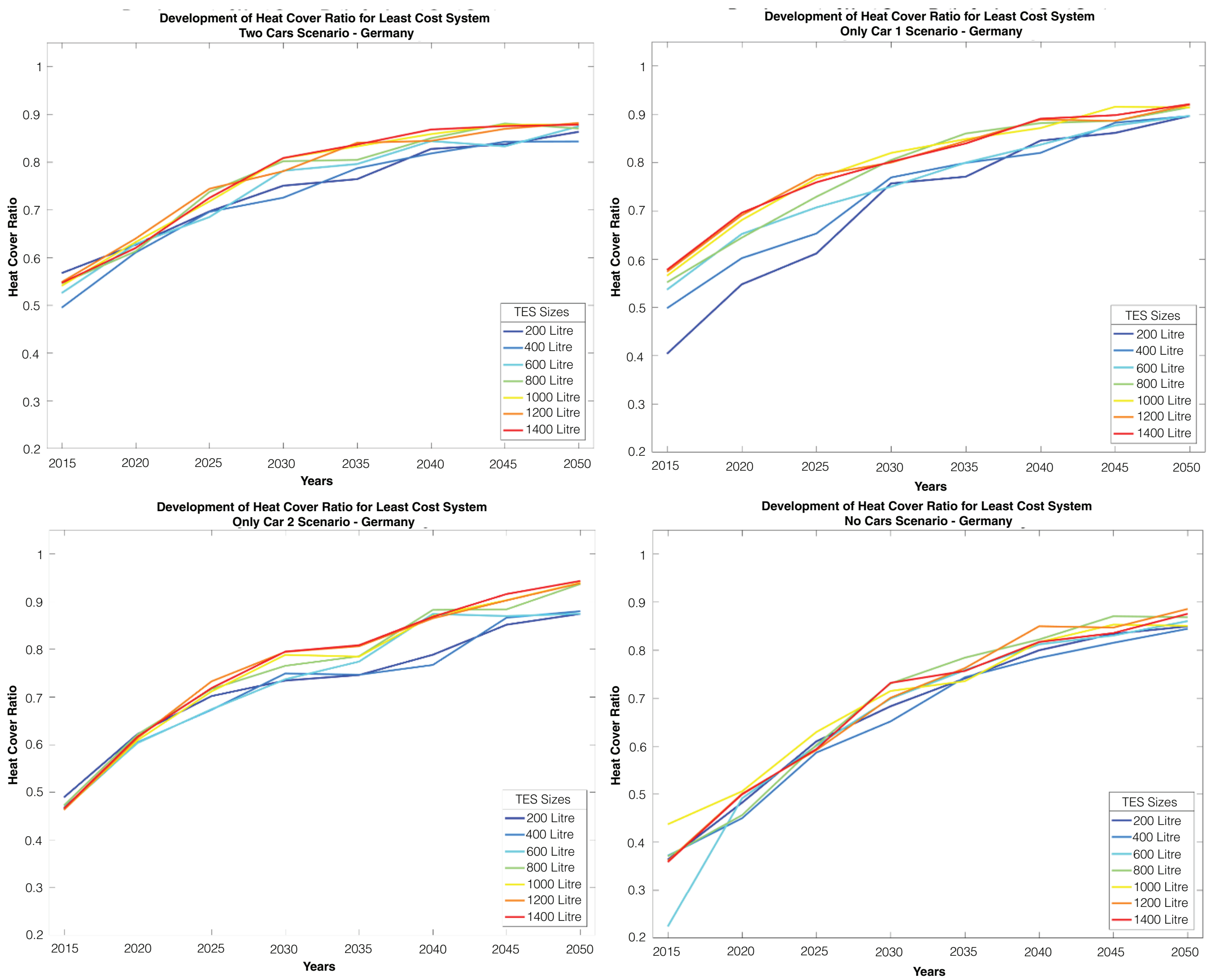

Figure A.6: Development of HCR of the single-family system for the ’Two Cars Scenario’ (top left), ‘Only Car 1 Scenario’ (top right), ‘Only Car 2 Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right)

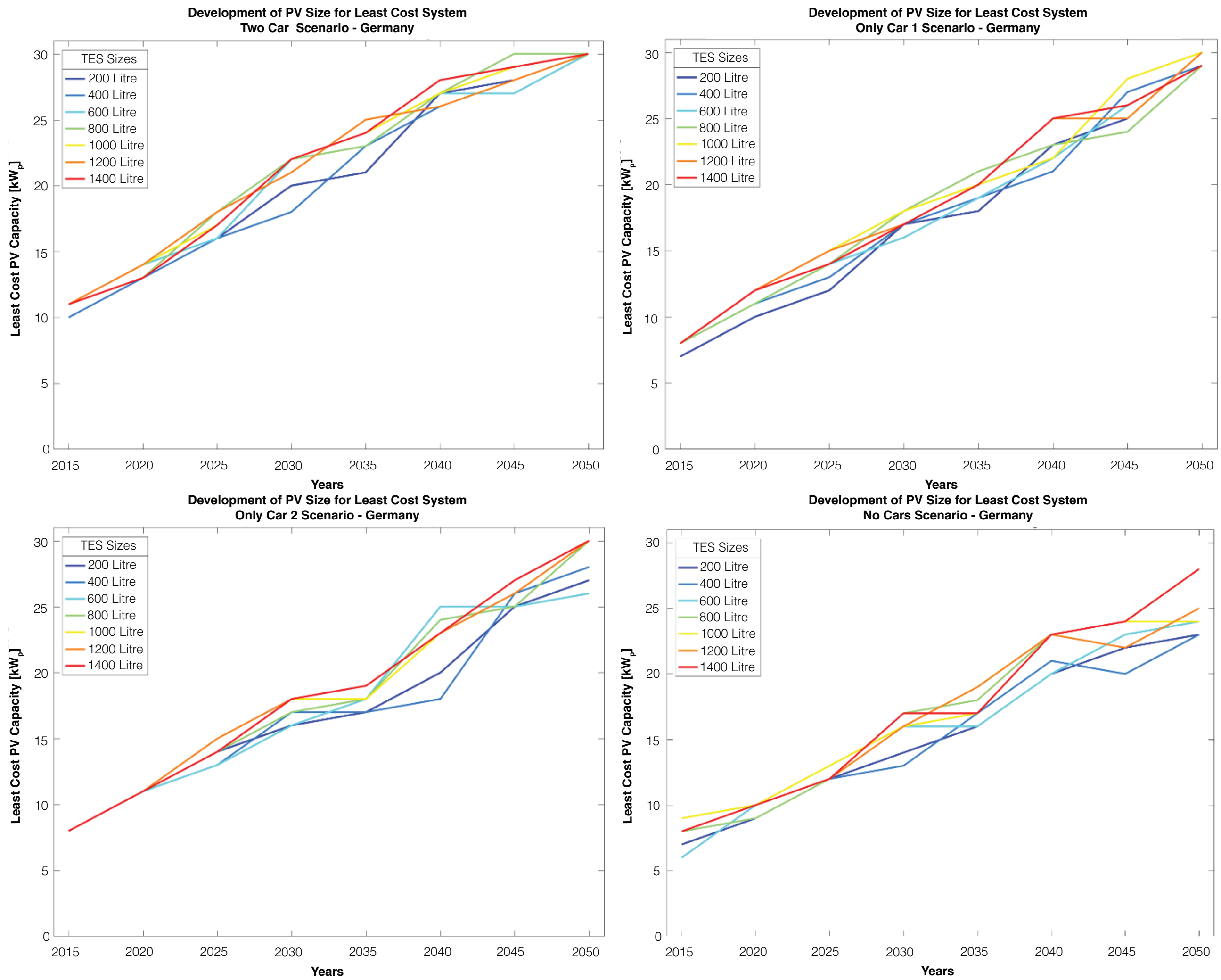

Figure A.7: Development of the least cost system PV capacity of the single-family system for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right)

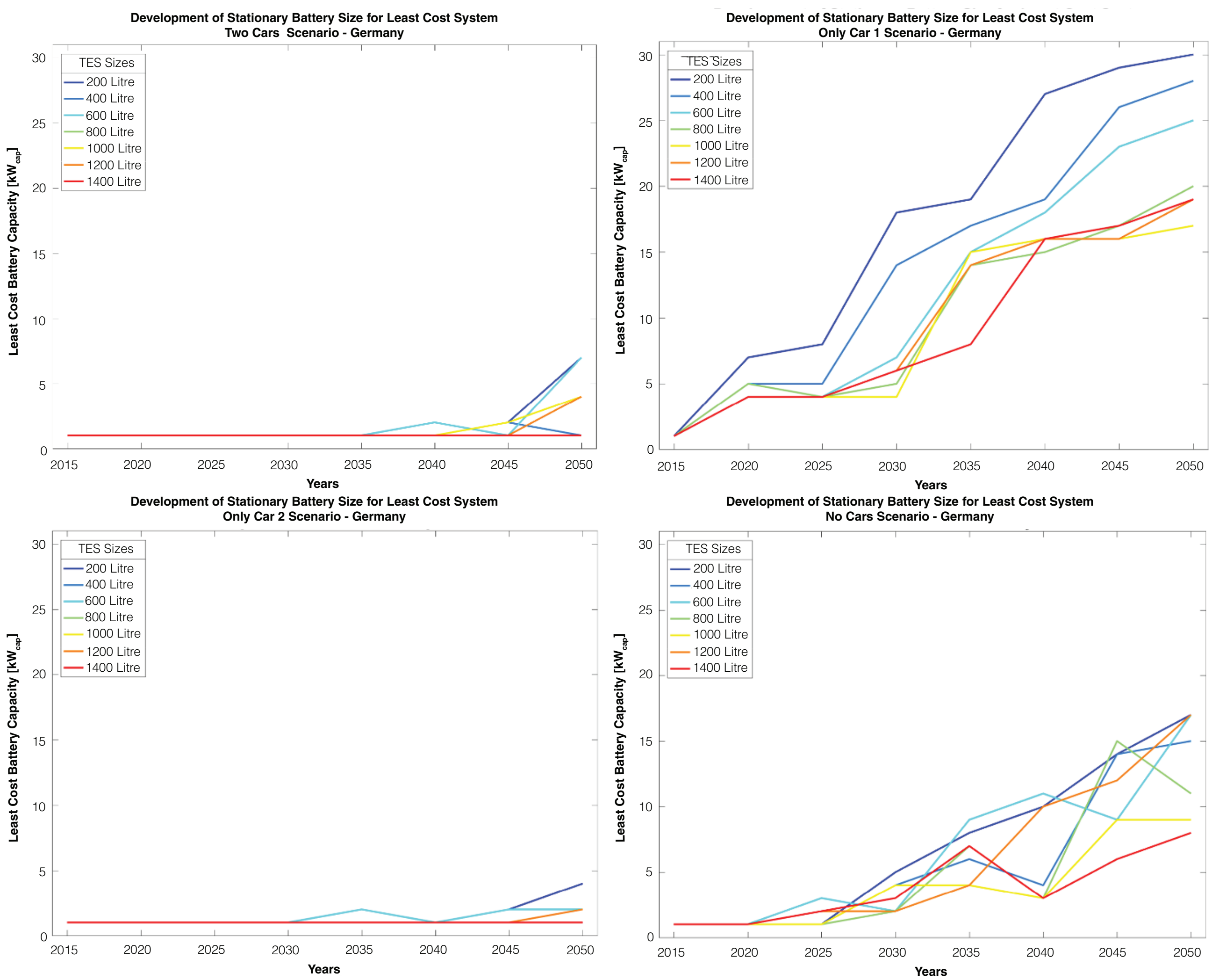

Figure A.8: Development of the least cost system stationary battery capacity of the single-family system for the ’Two Cars Scenario’ (top left), ‘Only Car 1 Scenario’ (top right), ‘Only Car 2 Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right)